MIE346 – Design Assignment 3 (4%)

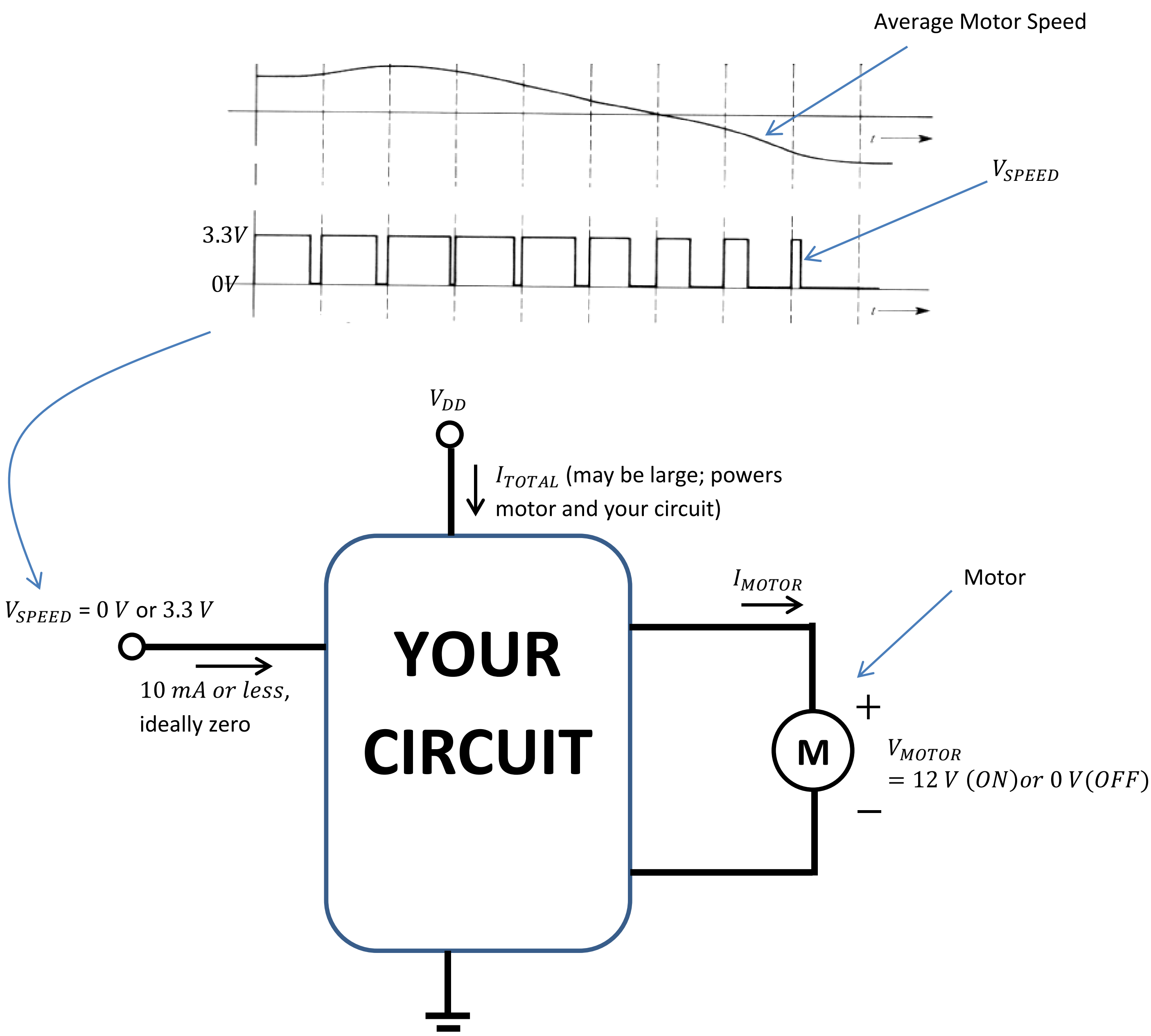
Due Date: Mar. 26th, midnight (online submission)

In class we will be learning about various applications of MOSFETs, which will be the focus of this design assignment. In one common application, we are able to use the transistor as a **switch** to turn a large load on and off. In this application, the transistor dissipates very little power in either state (on or off), and thus the circuit is very efficient as well. If the load is turned on and off very rapidly, we can even achieve a form of proportional adjustment by changing the relative amount of time per cycle spent on and off – this is called pulse-width modulation.

- You have a **DC brushed gearmotor** that you wish to speed control:
  - http://www.robotshop.com/ca/en/lynxmotion-12v-90-rpm-9911oz-in-1269-brushed-dc-gear-motor-w--encoder.html
- From the specifications, this motor may draw from $250\,mA$ of current (no mechanical load) up to $10.0\,A$ of current (stall speed, maximum torque). On the average, it draws $1.58\,A$ of current when operated near its most efficient speed. It is a 12V motor, meaning it can be supplied with any voltage from $0\,V$ to $12\,V$ without damage.
- In order to control the speed of the motor, you initially think about different methods. One would be to use something like a potentiometer or resistor divider. However, you determine this is too inefficient – significant amounts of power would be lost as heat in the resistors. Instead, you decide to use **pulse-width modulation**; that is, your circuit will operate the motor either fully ON (supply close to 12V to the motor) or fully OFF (supply 0V to the motor). By switching between these two states very rapidly (at $f \gg Motor\ Speed$), and by varying the relative amount of time spent in the ON state relative to the OFF state per cycle, you can achieve speed control with high efficiency.
- Thus, your goal is to design a circuit as follows:
  - Your circuit is powered by a single supply voltage, called V_{DD}. You may select this voltage to be any value your circuit requires. This is a high current supply, meaning it can provide as much current as is needed. However, care should be taken in that your circuit should not apply more than $12\,V$ across the motor wires/pins at any time.
  - The circuit has a **speed control input**. This voltage input has only two states, representing when the motor should be 'ON' and 'OFF'. The 'ON' state is taken when $V_{SPEED} = 3.3\,V$. When in the 'ON' state, your circuit should apply $12V$ across the motor terminals. Similarly, the 'OFF' state could happen when $V_{SPEED} = 0\,V$, in which case the circuit should deliver $0\,V$ to the motor as well. However, if it is beneficial to your design, you may reverse the values of V_{SPEED} which relate to 'ON' and 'OFF' (that is, you are allowed to instead select $V_{SPEED} = 0V \rightarrow MOTOR\ ON$ and $V_{SPEED} = 3.3V \rightarrow MOTOR\ OFF$). The behaviour of your circuit when V_{SPEED} is neither $3.3V$ nor $0V$ is not defined, and so you can assume it will always be one of these two values. Very little or no current ($< 10\,mA$) should flow into this input.
  - Since the motor voltage is zero in the 'OFF' state, your circuit is naturally efficient in this state (no power is drawn by the load). However, in the 'ON' state, you should select your components such that the **efficiency** of your circuit is at least 95%. That is, you have a single supply voltage, V_{DD}, that powers the motor and your circuit. If the motor and circuit together draw I_{TOTAL} current, then the total power used by the motor and circuit together is $P_{TOTAL} = I_{TOTAL}V_{DD}$. Similarly, the power used by the motor alone is $P_{MOTOR} = V_{MOTOR}I_{MOTOR}$. Note that V_{MOTOR} should be close to $12\,V$ when the circuit is in the 'ON' state. Efficiency is the fraction of total power delivered to the load (the motor):

$$\eta = Efficiency = \frac{P_{MOTOR}}{P_{TOTAL}} \times 100\%$$

- As a note about the above, please be careful not to confuse the efficiency of your circuit with the motor's efficiency (listed in the provided link). The motor's efficiency refers to the conversion of electrical energy into mechanical motion, and is not used in any calculations in this assignment.
- All components should be selected to take into account real-world limits. That is, the circuit should be designed to not have any device exceed its maximum ratings for power, current, or voltage. To keep costs and complexity limited, the circuit should not use any op-amps or specialized integrated circuits – only MOSFETs and passive components are needed.
- A rough sketch of the system looks like the following:



Research Keywords: PWM (pulse-width modulation), motor driver, speed control, level shifter

See Also: Lab 4 pre-lab/guide, MOSFET selection guide

Engineering Specification and Conceptual Design

1. Many of the details of the circuit have been given already in the earlier bullet points. For your specification, write a **brief point-form summary of the inputs and outputs of your system**. Try to fill in any missing details, for example your chosen design limit for output current to the motor.
2. As a hint towards solving this problem, you should be aware that most MOSFETs do not reach their rated $r_{DS_{ON}}$ value for triode mode until V_{GS} is significantly larger than V_T. For this reason, you may find a two-stage solution (using two MOSFETs) easier to design (as this will allow you to more easily create a large V_{GS} for the output-stage transistor). Draw a **block diagram** of your planned circuit – show the input and output connections for each block, and sketch example signals in the circuit or show voltage ranges of signals as appropriate.

Detailed Design

3. Start with the **output** of your circuit. Select a **circuit topology** (style of circuit) to drive the load (motor). In particular, you may want to research common source and common drain configurations, wherein you connect the motor as a load to the drain or to the source respectively. Each has different design considerations when selecting V_{DD}, the MOSFET type (NMOS vs. PMOS), and so on. Other configurations may be possible as well. Once you have selected a topology, **sketch the circuit diagram** of the output stage of your design.
4. Select a **real-world MOSFET** (from a common supplier, such as Digikey, Mouser, etc. as in the prior design assignment) based on the requirements you defined in Steps 1 and 2 and the circuit from Step 3. The selection of this MOSFET will heavily influence your efficiency, so be prepared to revise your selection if it later proves infeasible.
5. For the two states of your output circuit (motor ON and motor OFF), **solve the circuit you drew in Step 3 for all voltages and currents**. The input needed for your circuit to be in the 'ON' or 'OFF' state may not necessarily be $0\ V$ or $3.3\ V$ if you are planning a two-stage circuit, in which case you may input values for now. Calculate and verify that you have met the **efficiency requirement** at this point. You may want to allow some margin of safety on this requirement, as part of your circuit has yet be designed, and it will require power from the supply too, reducing overall efficiency slightly.
6. Continue by **selecting a circuit topology** for any remaining stages. Typically, other stages may be involved in shifting the level or range of voltage (say, from $0 - 3.3V$ to something higher to drive the output stage). These stages should not draw significant current from the supply, as they are not powering the load directly, and thus do not need to output significant current. Similarly, at the input to your circuit, V_{SPEED}, you should select values such that for both values of V_{SPEED} the current into the input is small (less than $10\ mA$, ideally near zero). **Sketch this intermediate circuit diagram**.
7. **Select real-world MOFSETs and component values** for your circuit from Part 6. Solve your circuit from Part 6 for the two input values of V_{SPEED} by **finding all voltages and currents**. Confirm that the circuit generates the correct output voltages needed to drive your subsequent circuit stage.
8. Draw the **complete schematic** of your finished design, if you have not done so already. Feel free to add other features you wish to include, such as a protection diode at the motor, at this point. With the circuit stages fully connected together:
    a. Verify (through whatever calculations you deem necessary) that the two inputs, $0V$ and $3.3V$, still generate the two distinct output states (ON, where the motor voltage is approximately $12\ V$, and OFF, where the motor voltage is zero).
    b. Verify that you still meet the efficiency requirement.